Blue devices shine as brightly as the weather at ISCS 97

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Exciting developments in various fields, from blue LEDs and VCSELs to RF power devices, were highlighted at the 24th International Conference on Compound Semiconductors (ISCS). This meeting was held from 7–11 September in San Diego, California, USA.

San Diego is a popular destination for most Americans and also for many international visitors. As usual, good weather was on hand, but a little warmer and more humid than is customary for this city. In keeping with the weather, the technical climate at the conference was also quite hot, with interesting developments offered in a variety of compound semiconductor technologies. This year over 300 papers were submitted, with 135 accepted as oral and invited papers and 35 for poster presentation. Attendance was 275, with Europe and the Pacific Rim regions accounting for about 20% each and Germany and Japan providing the largest contingents, with over 10% each.

The Conference Chairman, Herb Goronkin from Motorola, opened the conference plenary session. He noted that gallium arsenide devices had come a long way in the past 15 years to where every garage door opener now uses GaAs-based circuits. The invited papers were topical and informative, and provided insight into the commercial uses for compound semiconductor materials on the one hand and to their still untapped potential on the other. In one of the currently very active fields, short wavelength light emitters now provide commercial LEDs in quantity and are teasing the world with potential uses for blue-violet lasers.

As an example of one of the most rapid commercial semiconductor success stories, the short and successful history of blue emitters, LEDs to lasers, based on the gallium nitride materials system, was presented by Shuji Nakamura of Nichia Chemical Company Ltd, Japan. Nichia announced its first blue LED in 1993, followed by the first single quantum well LED in 1995 and the first multiquantum well device in late 1996, and it is now at production levels of 10 million blue diodes per month. This must be the fastest ramp-up in history of LED production.

Nakamura also provided a summary of Nichia's latest achievements in this technology together with that from other research groups. He demonstrated a working, high brightness, white LED emitting five lumens per watt (by using a blue LED and an yttrium aluminium garnet phosphor), the latest near-violet diode laser. In spite of the fact that the first pulsed operation of a blue diode laser was only reported in November of 1996, he reported the continuous wave (CW) operation of a blue-violet laser diode that has now been operating for 1000 hours and is still running. This level of reliability now appears to overshadow the work on the zinc selenide based blue-green lasers. There is still the ready market waiting for the winner! For all these devices, indium gallium nitride is used for the active layers, aluminium gallium nitride is used for the cladding layers and a light-transmitting layer is used for the p-electrode.

The other research groups from Cree, Fujitsu and the University of California at Santa Barbara have recently reported the operation of short wavelength visible diode lasers. These blue lasers have now been made on a variety of substrates, including 6H silicon carbide, magnesium aluminate and sapphire, and they now operate at lower threshold voltages and currents (as low as 16 mA, or 1.5 $kA.cm^{-2}$) and over a wider wavelength range (390 to 440 nm) than the first 400 nm laser.

The notable phenomenon of gallium nitride technology is that all the high-brightness devices have been made from materials with defect levels in the 11×10^{10} range, whereas other typical III-V materials will not emit at defect levels above the 5×10^{10} range. Additionally, green and blue nitride-based LEDs are both being used commercially. Ecology may also enter the end-use equation, since the nitride-based emitters are relatively nontoxic when compared with gallium phosphide and gallium arsenide based devices.

The second plenary lecture was given by Lou Tomasetta, president and CEO of Vitesse Inc of Camarillo, California. The title of his talk was 'The Commercialization of the Semiconductor of the Future', the old name for gallium arsenide. He led the audience through over 20 years of history - the early years of advanced development (1975 to 1983), when microwave FETs, simple gates and bulk crystal growth were the order of the day - early manufacturing days (1983 to 1992), when digital ICs were demonstrated without any system useable chips and when 'insane market forecasts' indicated that commercialization would be easy - to the final goal, market-driven commercial ICs (1992 to 1997).

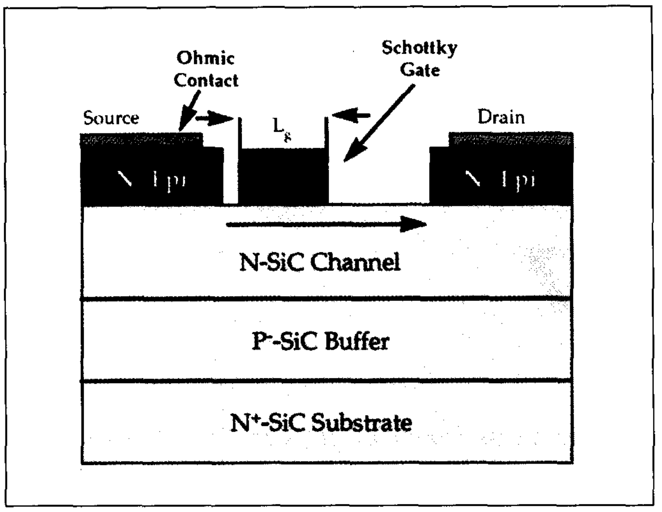

Figure 1. Cross-section of SiC MESFET demonstrating RF power densities of 850 W.mm^{-2} at 850 MHz CW and 10 GHz pulsed operation. Electrons flow laterally from source to drainconfined to the n-type channel by the P- buffer lever and controlled by the Shottky gate. (Courtesy of C. Weitzel, Motorola.)

These three periods correspond to other drivers of the GaAs IC development story, where the market was defence-driven for military satellite applications from 1977 to 1982, and was technology-driven by Cray and Convex from 1982 to 1992. From 1992 to 1994, the GaAs integrated circuit became a CEO's nightmare as revenue dropped 30% and all lost money - Vitesse posted a $15 million loss in 1993. Layoffs and mergers became the order of the day as cash flows shrank. Then in 1995, happy days, three years later than forecast, the markets exploded with a doubling of sales as the market changed to a telecommunications-driven situation; this market segment now accounted for more than 50% of sales. And now the impossible has happened, the total 1997 GaAs IC market sales exceed $300 million per year, over a million transistors per chip has been achieved, together with 2 ns access times and 64K RAM circuits made on 6″ wafers. These circuits are pin-identical equipment to a CMOS chip, with costs in the region of 0.001 cents per gate.

The gallium arsenide IC market is now the healthiest it has ever been. The 1997 sales year is almost over and the total GaAs circuit sales will be double those for 1996, with digital ICs at $150 million, RF and analog devices at $300 million and transistors at $250 million. Although the following are 'only forecasts', never to be trusted in the past, the industry now wants to believe them. Thus, between 1996 and the year 2000, the communications segment (SONNET, Fibre Channel, ATM and Gigabit Ethernet) are expected to grow by a factor of five or six. The wireless segment (PCS, GSM and wireless LANs) is expected to grow by factors of between five and ten. To supply these market needs there are a wide range of transistor technologies available such as MESFETs, HBTS and pseudomorphic HEMTs.

Tomasetta also stated that by the year 2000 the manufacturing processes will need to become more efficient along with this market growth as the market is demanding ever-improving cost performance goals. Part of this increased manufacturing efficiency will be derived from a changeover from 4″ to 6″ wafers, which is planned for 1998.

As more research is performed on the gallium nitride materials system new items of interest turn up. O. Brandt of the Paul Drude Institut in Berlin, Germany, reported on the different growth results obtained by MBE on cubic gallium nitride surfaces. One of the interesting properties was the segregation of indium during the growth of gallium/indium nitride films at 620°C, with variations of 4% in indium content (i.e. from 7 to 15%); the other was the fact that 10% less indium was required than on hexagonal substrates to obtain emission at the same wavelength.

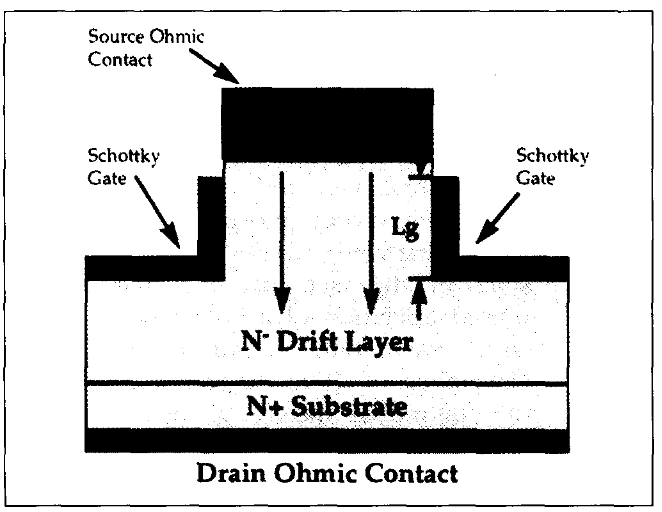

Figure 2. Cross-section of a new SiC SIT which shows the highest total power output for an RF power device. (Courtesy of C. Weitzel, Motorola.)

In the light-emitting department, G.E. Hoefler from Hewlett Packard described the latest orange LEDs for traffic lights. By re-designing the transparent-substrate package to obtain higher levels of heat removal, packaged LEDs emitting 19 lumens at 590 nm can be made. Only 20 to 30 of the new LEDs will be needed for an amber traffic light to replace 300 to 500 of the previous generation of 'high brightness' LEDs required for the same application.

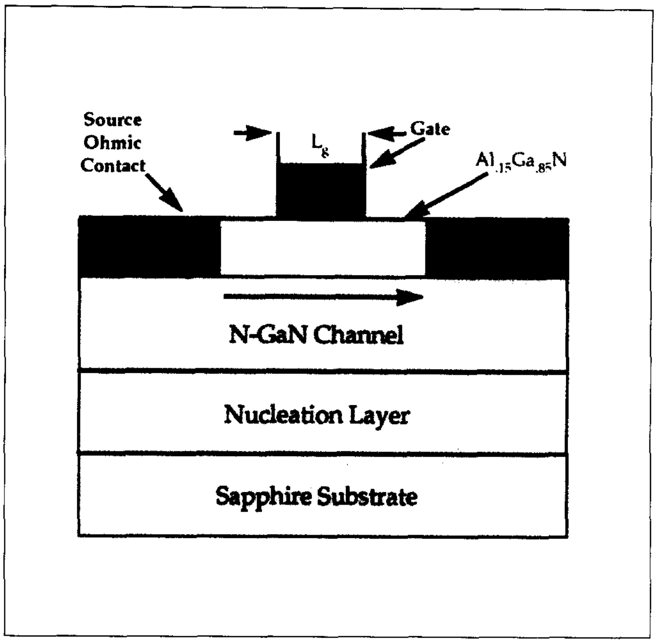

Figure 3. This AlGaN HFET design holds the the record for the highest frequency of operation. (Courtesy of C. Weitzel, Motorola.)

Another on-going technology development in the III-Vs area is the use of deposited oxides for metal-oxide-semiconductor (MOS) devices and for the rapidly growing use of vertical cavity surface emitting lasers (VCSELs). S.A. Feld from Wright State University, Ohio, USA, reported on the 350°C steam oxidation of aluminium gallium arsenide layers, which has become a critical step in the production of VCSEL devices. VCSELs are becoming the preferred laser type for fibre optic communications systems, rather then edge-emitting chips, because better confinement is obtained and it is easier to match the beam aperture with the fibre.The best results were obtained from 1 μm oxides grown slowly under relatively low pressures (5 torr). D. Bimberg from the Technical University of Berlin extended the oxide VCSEL technology to quantum dots, MOCVD-grown in gallium aluminium arsenide. As the dots sizes became smaller, the wavelength of the light became shorter, for example from 980 to 960 nm. Edge-emitting quantum dots that operated at room temperature were also described. Deposited and grown oxides have now been used to make the first compound semiconductor MOSFETs.

Erbium doping continues to be a topic of interest in the fibre optic industry, because of the efficiency of 1.55 μm wavelength range light emission of the Er^{3+} ion - the wavelength used for most long-distance fibre transmissions. Y. Fujiwara and co-workers from Nagoya University, Japan, have extended their earlier work on erbium-doped indium phosphide to gallium phosphide and reported 'extremely sharp' erbium-related photoluminescence (PL) from OMVPE-grown gallium phosphide using erbium tris-methylcyclopentadienyl as the erbium source. The light spectra varied with the growth conditions, but the erbium content was almost constant. PL at 1.54 μm from multiple erbium sites was described by S. Kim from the University of Illinois in MOCVD-grown gallium nitride.

In the solar cell arena, the National Renewable Energy Laboratory (formerly SERI), of Washington DC, USA, offered the answer as to why heavily defected copper indium selenide is such an efficient and stable solar cell material. Their research efforts have revealed that this compound material can tolerate relatively large off-stoichiometric compositions. Thus, copper single-negative and indium double-positive defects exothermically form very stable defect pairs with no deep level defects. Therefore, copper-poor indium copper selenide spontaneously forms these stable complexes and provides an efficient photovoltaic material. No interstitial copper atoms were detected, therefore there is no diffusion of copper in copper-poor layers.

C. Weitzel from Motorola presented a review of the exciting developments in the field of RF power devices derived from the wide bandgap materials. To date, the highest RF power density (850 W per mm at 850 MHz CW, and at 10 GHz pulsed) was demonstrated by a 4H-silicon carbide MESFET, the highest total power (450W pulsed at 600 MHz and 38 W pulsed at 3 GHz) has been produced by a silicon carbide SIT (a static induction transistor, developed by Westinghouse), and a QW aluminium gallium nitride HFET (heterojunction FET) holds the record for the highest frequency of operation with an f_{max} of 97 GHz. In this last case, aluminium gallium nitride on a silicon carbide substrate turns out to be two times better than silicon carbide. Cross-sectional diagrams of these devices are shown in Figures 1, 2 and 3, while f_{max} data are presented in Figure 4.

In a development moving wide bandgap devices towards power control in the real world, a silicon carbide power module containing four SITs has been shown to have a one kilowatt capability at 600 MHz. As may be expected, commercial silicon LDMOS (laterally diffused metal oxide silicon) FETs provide the lowest cost power devices, but their operating frequency is under 1 GHz. In a later paper, K. Chu from Cornell University anticipates a good performance potential from aluminium gallium nitride HFETs. Thus, as wide bandgap device technology develops, its related devices are expected to play an increasing role in RF power generation.

The high-temperature operation of semiconductor devices has long had interest for industrial applications. Another step forward was made when K. Lipka, reporting results of a collaboration between researchers at Motorola, UC Santa Barbara and the University of Ulm, demonstrated the operation at 500°C of a gallium arsenide HFET made at low temperatures. The performance of these devices decreased a little with increasing temperature such that the output current fell only by about 10%, from 380 mA at room temperature to 350 mA at 500°C and the pinch-off voltages increased from 2.4 to 2.5 V respectively, showing a potential for commercial devices. Above 500°C the circuit performance declined rapidly, but the chips could be heated up to 540°C and regain their performance after cooling. After heating above 570°C permanent degradation occurred.

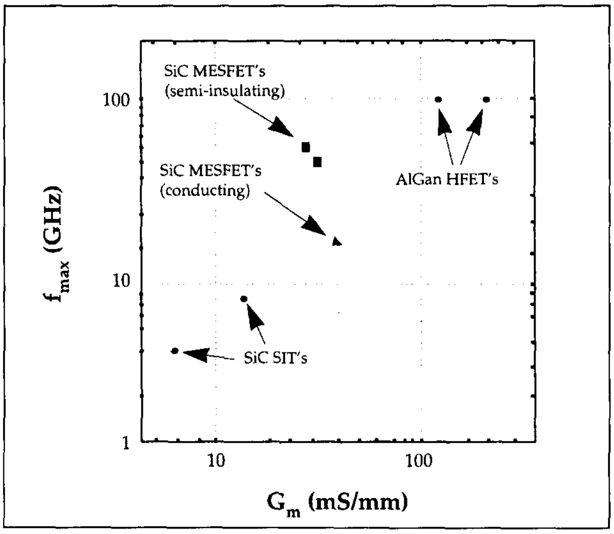

Figure 4. Frequency, f_{max}, data for SiC SITs, SiC MESFETs and AlGaN HFETs. (Courtesy of

The potential for compound semiconductor devices continues to grow, so it will be on to ISCS 98 in Japan for the latest achievements in ICs, power devices, RF circuits in the high frequency atoms, plus the successes in the blue and green LED efficiency ratings.